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Solar thermal water pumping systems: a review

Y.W. Wong, K. Sumathy*

Department of Mechanical Engineering, University of Hong Kong, Hong Kong

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Abstract

A number of attempts have been made by scientists to utilize solar energy for irrigation water pumping. It is mainly a problem of conversion of heat energy available from the sun, to mechanical energy. Some ingenious methods have been devised to utilize the available energy at low temperatures. This paper reviews past efforts to develop solar thermal water pumping systems which employ either conventional pumps or unconventional pumps, and emphasizes how the system modifications were made to suit different pumping conditions and requirements.

1. Introduction

Solar pumps are of special significance in countries where the farming communities are scattered over large and distant areas and where electrical power is not readily available. This would include most of the countries in Asia, Africa and Latin America. On account of the large distances involved and the low energy requirements, transmission of electrical energy from large central power stations becomes an uneconomic proposition. Use of oil engines requires transportation of oil to the remote areas which, again, is not economical. Besides, the skilled help for maintenance of oil engines may not be readily available in the remote areas. Under these circumstances, the power for irrigation must come from local energy sources. Besides animal power, solar and wind energy and to some extent biogas may provide the solution to this problem. Wind energy and biogas are derived from solar energy and therefore can be considered as part of solar energy [1].

A number of attempts have been made in different countries, to use solar energy for pumping water. These attempts have used different principles and have been

* Corresponding author. Fax: 00 852 2858 5415

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successful to varying degrees. Mechanical energy needed for pumping water may be produced by either thermodynamic, or direct-conversion methods [2] as illustrated in Fig. 1.

1.1. *Thermodynamic methods*

In the solar conversion scheme any solar collector, including concentrators, may be employed to produce a fluid at high temperature and pressure. This fluid at high pressure may be either utilised directly in the form of Rankine, Brayton or Stirling cycle, or indirectly by using a secondary working fluid. The mechanical energy produced may operate a conventional or an unconventional pump.

1.2. *Direct conversion methods*

The direct conversion of solar energy involves the use of photovoltaic, thermoelectric or thermionic processes to produce direct current electrical energy, which may be used with d.c. motors or converted to ac through inverters, and then to operate the water pumps. Among the direct conversion methods, one of the popular applications is solar photovoltaic (PV) powered pumping which has a long lifetime, little maintenance and is relatively more compact in size. However, large scale PV

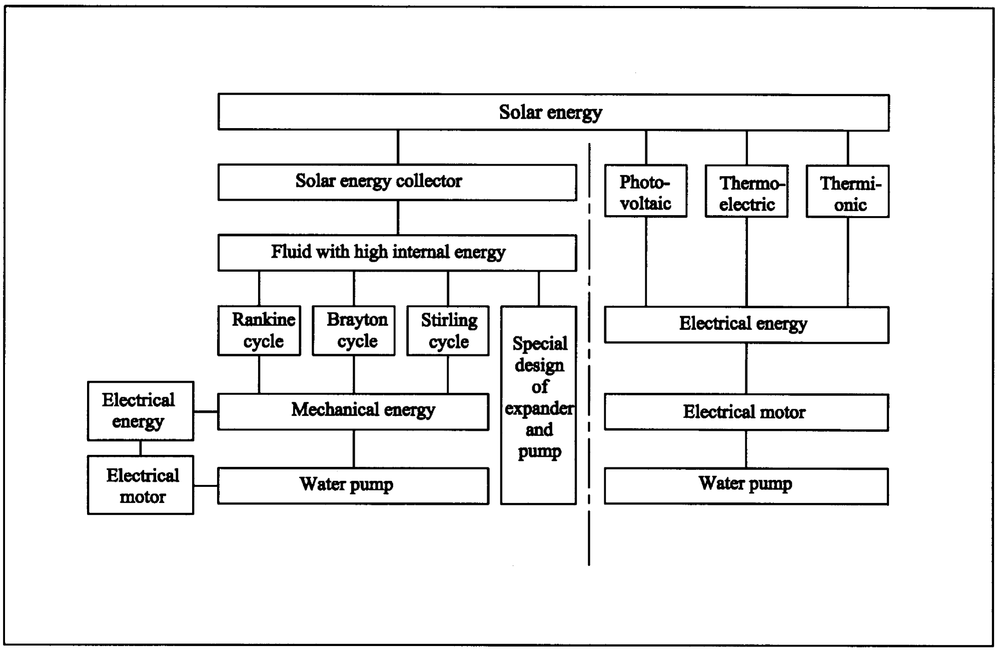

Fig. 1. Solar water pumping chart.

arrays continue to be expensive. The present market cost of the cells is 4–5 U.S. \$/peak watt [3]. Their use for agricultural pumping is probably a distant possibility.

1.3. *Past efforts and scope of the present study*

In recent decades, some solar pumps operating on the principle of thermodynamic conversion scheme have been built and tested extensively throughout the world. These pumping systems utilize the thermal energy from the Sun to run a conventional water pump or specially designed expander to achieve pumping of water. In the 1970s and 1980s, several review studies were conducted [2, 4, 5] on numerous solar thermal water pumping systems. However, many new designs have been introduced recently and the developments in this field need to be updated. It is the objective of this paper to review various attempts to produce solar thermal water pumps and to compare their performances. Emphasis is placed on how modifications were made to suit different pumping conditions and requirements. This review may provide a useful reference for researchers and designers attempting to develop new systems in this field of work.

The following text describes the operation of several solar thermal water pumping systems and their performances. The first part focuses on the conventional pumping methods in which the internal energy of the working fluid is used to drive a conventional pump, such as a centrifugal pump. The second part of the work presents the unconventional pumping methods in which the internal energy of the working fluid is used to operate a specially designed expander to pump the water to the required discharge head. The greatest advantage is that it does not involve any mechanical moving parts to operate the whole system and this is explained later.

2. Conventional pumps

2.1. *Theory*

The working principle of a solar thermal water pumping system coupled with a conventional pump can be explained clearly by considering a simple Rankine-cycle water pump as an example [2]. The cycle shown in Fig. 2 is a Rankine-cycle solar pump. The expander may be a reciprocating engine, a turbine, or any other device, which can convert the vapour's total enthalpy to mechanical energy. The collector may be a conventional flat-plate collector, a reflective/refractive-type of concentrator, or even a solar pond. With the flat-plate solar collectors, the primary liquid going through the collector may be pressurized water where temperatures as high as 150°C may be reached in some designs. The circulating pump, P_1 may be eliminated and the cycle circulation be maintained through thermosyphon action. Because of the low temperatures involved in the flat-plate collectors, low boiling-point organic fluids should be employed as the primary or secondary working fluid. With the concentrators, where temperatures around 300°C can be achieved, the fluids going through

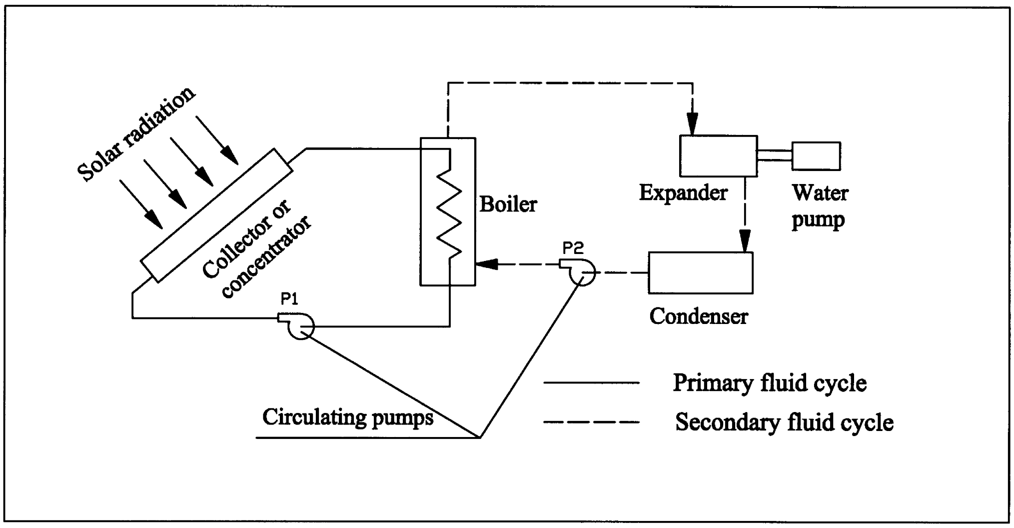

Fig. 2. Schematic of Rankine-cycle solar water pump.

the collector and the expander may be different from each other, or the same fluid may be used in both. The following pump designs are selected examples.

2.2. *Centrifugal pumps*

There have been many designs of small engines aiming at producing power for water pumping. Pytlinski [4] presented a report published in 1901. According to this report, a reflector was a truncated cone 10.2 m in diameter with a central opening of 4.6 m at the bottom. The inner surface was composed of 1788 small, flat mirrors arranged to approximate a conical surface. The mirrors reflected solar radiation on to the central tube boiler, 4 m in length, which held 380 l of water, leaving 200 l for steam. The entire boiler and reflector system were mounted on an equatorial axis, automatically clock-driven to follow the sun. The steam at high pressure drove an 8.2 kW compound steam engine belted to a centrifugal pump. At a pumping rate of 5300 l min^{-1} against a 3.6 m head, the system produced a peak power of about 7.46 kW.

Pytlinsk [4] also referred to the work carried out by Shuman who built a number of solar engines, some of which were used for pumping irrigation water. In 1907, he used solar energy to drive a 2.61 kW vapour engine using ether as a working fluid. A pond of area of 11.2×10^3 m^2 covered by glass was used to heat ether which was circulated in a heat exchanger immersed in the water. Ether vapour generated in this way ran an engine connected to a small centrifugal pump. A block diagram of the plant is shown in Fig. 3.

Tabor and Bronicki [6] built a 3.68 kW solar installation for pumping water. The system used a binary Rankine cycle with monochlorobenzine (C_6H_5Cl) vaporised by superheated steam from solar collectors. The vapour was led to a turbine to generate

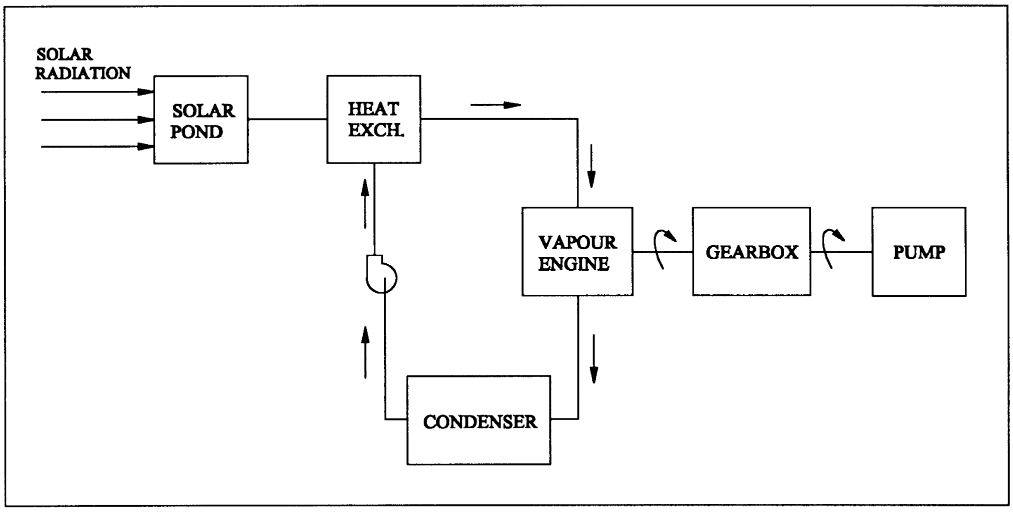

Fig. 3. Block diagram of Shuman's installation.

mechanical power. The plant could lift 11,300 l of water per day to a height of 45.7 m from a well.

Near Willard in New Mexico [4], a solar powered irrigation plant started operation in 1977. Parabolic trough collectors of area 622 m^2 with their axes mounted in a north–south direction provided energy for immediate operation and also for storage. The Rankine cycle with Refrigerant-113 as the working fluid operated at a peak temperature of 436 K, while both the primary fluid and energy storage fluid were 'Caloria HT-43'. While the peak temperature of 'Caloria HT-43' was 489 K, the storage volume was 22,700 l. The turbine running at 36,300 rpm powered a pump running at 1760 rpm through a reduction gear. The water pumped at a rate of 2600 l min^{-1} from a 34 m deep well could provide irrigation for approximately 405 m^2 of land.

Talbert et al. [7] have developed the world's largest known solar-powered irrigation-water system as shown in Fig. 4. The system was designed and built by the Columbus Laboratories of Battelle Memorial Institute. The pump was capable of developing 37 kW and could pump 38,000 litres of irrigation water per minute at peak operation. The system consisted of 554 m^2 of parabolic cylindrical solar collectors. The power required to drive high volume flow propeller pump was realised through a Rankine cycle using R-113 as the working fluid. The overall output was less than predicted. He pointed out that this could be traced to three factors: (i) the collector did not produce the required heat output for which the system was designed; (ii) the temperature of the water in the sump, used for cooling the vapour in the condenser was higher than anticipated and (iii) additional pipe bends and a flow meter resulted in more flow losses.

Figure 5 shows an interesting design of a solar hot air engine developed by Farber and Prescott [8]. The solar energy is focused on area A where air is heated and its

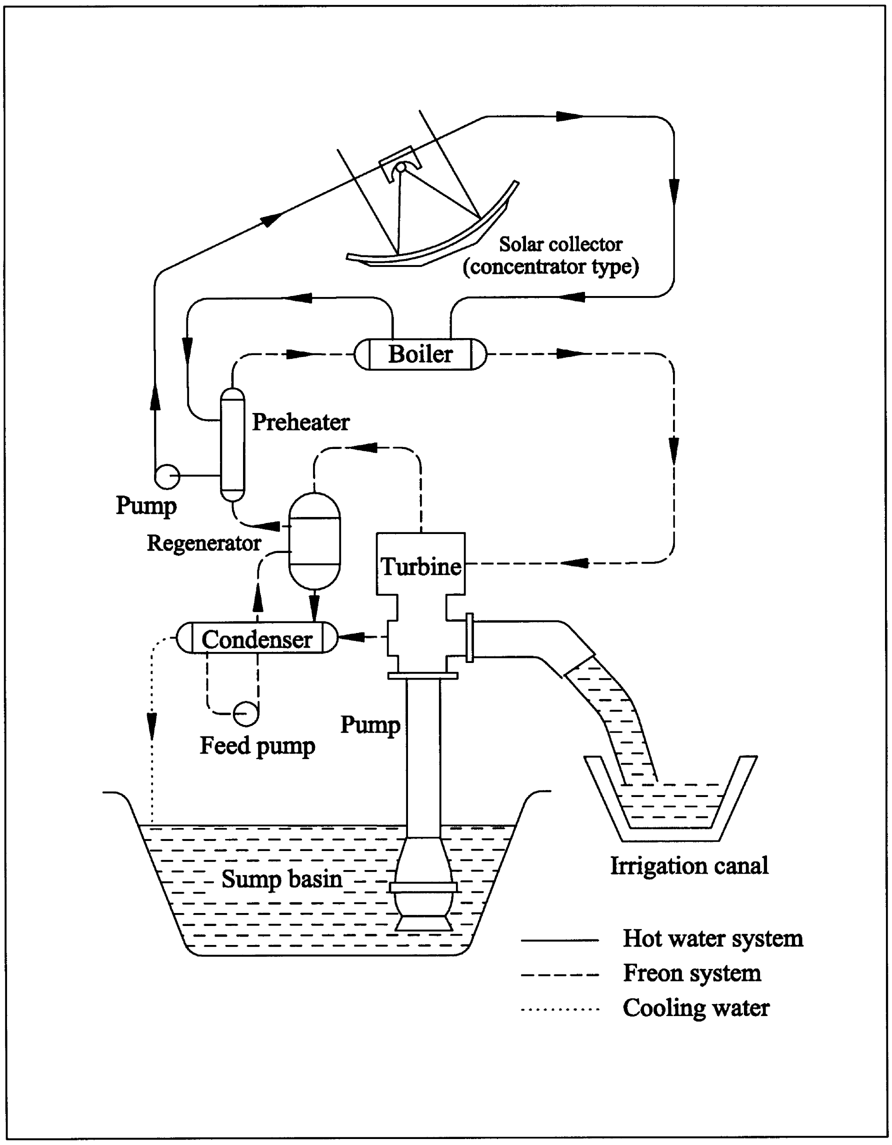

Fig. 4. Schematic of Talbert et al. [7] installation.

expansion pushes the piston, P, down. In the down-stroke of the piston the displacer, D, moves to the left by the linkage, L. On the up-stroke of the piston the displacer moves to the right and all the hot air is at the left section of the cylinder, B, and loses heat to the cooling water. An efficiency of about 9% is obtained at 100 rpm with a power of about 149 W.

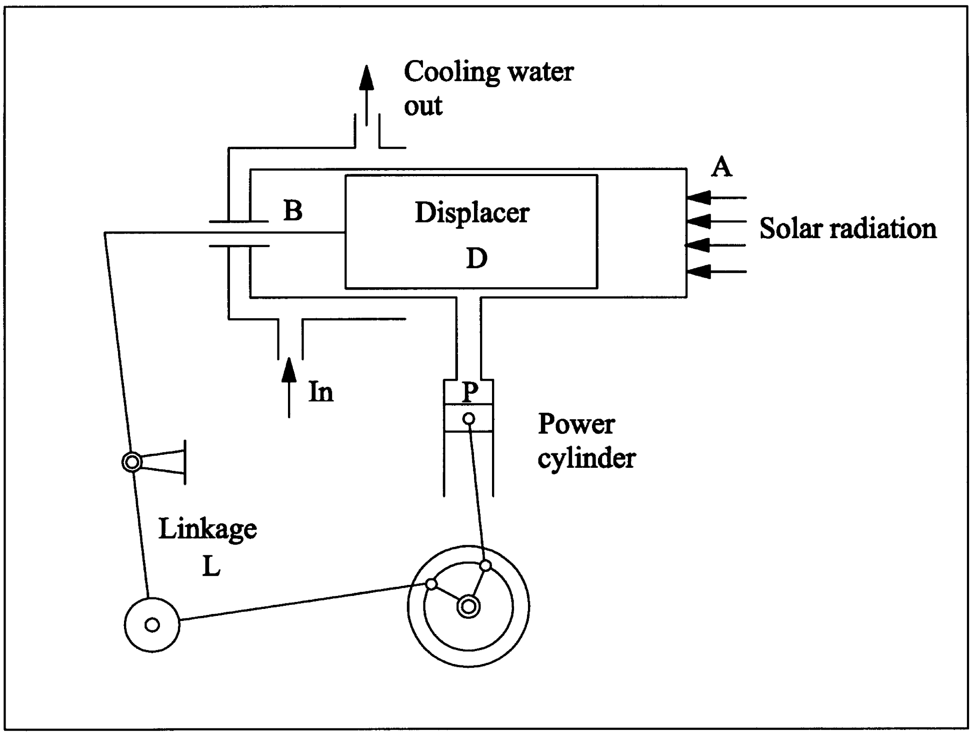

Fig. 5. Schematic diagram of the hot-air engine.

2.3. *Diaphragm pumps*

The earliest known experiment with a solar diaphragm pump was carried out by Tellier in the 1880s [9]. In 1983, Burton [10] published a technical note on his solar powered diaphragm. The primary fluid (water) was circulated between the collector array and a vapour generator in which trichloro-tri-fluoroethane (R-113) was evaporated. The pump was assembled on a stand 2 m above a water supply tank with provision for the discharge of water from the pump to a height of up to 3 m above the pump body. This pumping system was able to operate in a closed cycle, but the overall efficiency was low compared with that in an open cycle. With the help of a hydraulically coupled feed pump, the condensed working fluid was returned from the condenser to the vapour generator. On a clear sunny day with an average solar insolation of about 850 W m^{-2}, the water flow rate was found to be 14.6 l min^{-1} at an overall efficiency of 0.21%.

Another example of a diaphragm pump was investigated by Sharma and Singh [11] as shown in Fig. 6. They studied a model of a low lift diaphragm pump working with an automatic valve mechanism. The pump operated based on the Rankine cycle with freon-113 as a working fluid. The solar flat-plate collector used had an exposed area of 1.4 m^2. Liquid freon was vapourized in the collector and the vapour pushed a

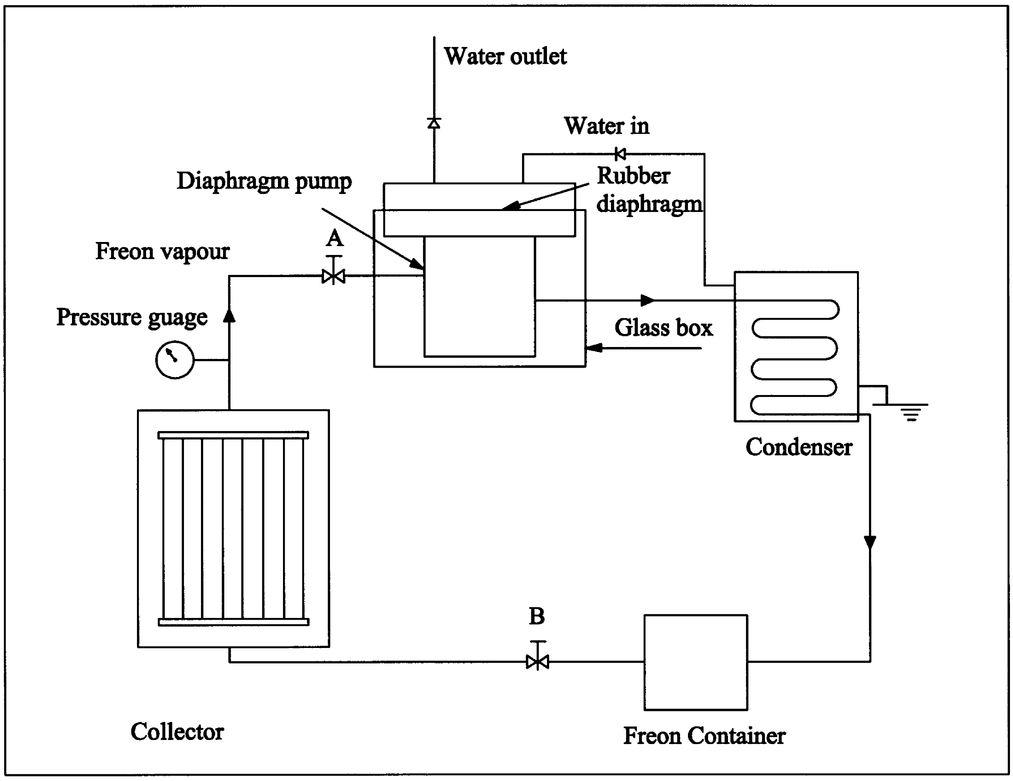

Fig. 6. Flow diagram of Sharma and Singh's diaphragm pump.

rubber diaphragm which in turn pumped the water. The exhausted vapour was condensed and collected in a container. The condensate was charged back into the collector for use during the next day's operation. Test results showed that with a constant input vapour pressure, the discharge of the pump decreased as the head increased. The discharge of the pump was 4.31 l min^{-1} at a 3 m head while it reduced to 2.81 l min^{-1} at a head of 6 m. This pump was suitable for a head of only 3–4 m. The most expensive part of the system is the working fluid, i.e. liquid freon. Some inexpensive fluid should be tried in further developmental stages. The most economical fluid would be water. But if water were used, then the collector would have to be modified such that it would generate steam. Therefore, such a system requires additional costs for modifying a collector to achieve a temperature of above 100°C. To determine the most feasible system the overall costs of the systems proposed have to be compared.

2.4. *SOFRETES systems*

Bahadori [2], in his review paper, reported a type of solar water pumping unit [6, 12–15] employed in several developing countries. The unit was manufactured by

SOFRETES of Montargis, France, and is shown schematically in Fig. 7. The first system of this kind was installed in Guanajuato, Mexico in 1976, the details of which were furnished by Anderson as presented in Pytlinski's literature review [4]. The installation employed 2499 m^2 of flat-plate collectors. Water was used as the primary heat transfer fluid. The heat was transferred from water to the working fluid (R-11). A vapour turbine and an electric generator produced 30 kW of electric power to drive two pumps. The station supplied about 1,000,000 l of potable water per day. It was also reported that SOFRETES had systems capable of producing 25 kW and 50 kW power output.

Another SOFRETES unit investigated by Masson and Girardier [14] has been functioning in Dakar, Senegal, with the following characterisitics: the collection area, 330 m^2; the motor effective speed 80–90 rpm; water temperature leaving the solar collector, 65–80°C; water temperature in the well, 28–30°C. The pumping capacity was found to be 8–10 l min^{-1} at a discharge head of 13–14 m, while the corresponding power was about 21 W.

Gupta et al. [16] have developed a solar pumping system, operating on a low temperature organic Rankine cycle. The SOFRETES piston engine was coupled to flat-plate solar collectors through a boiler and condenser on one side and to a

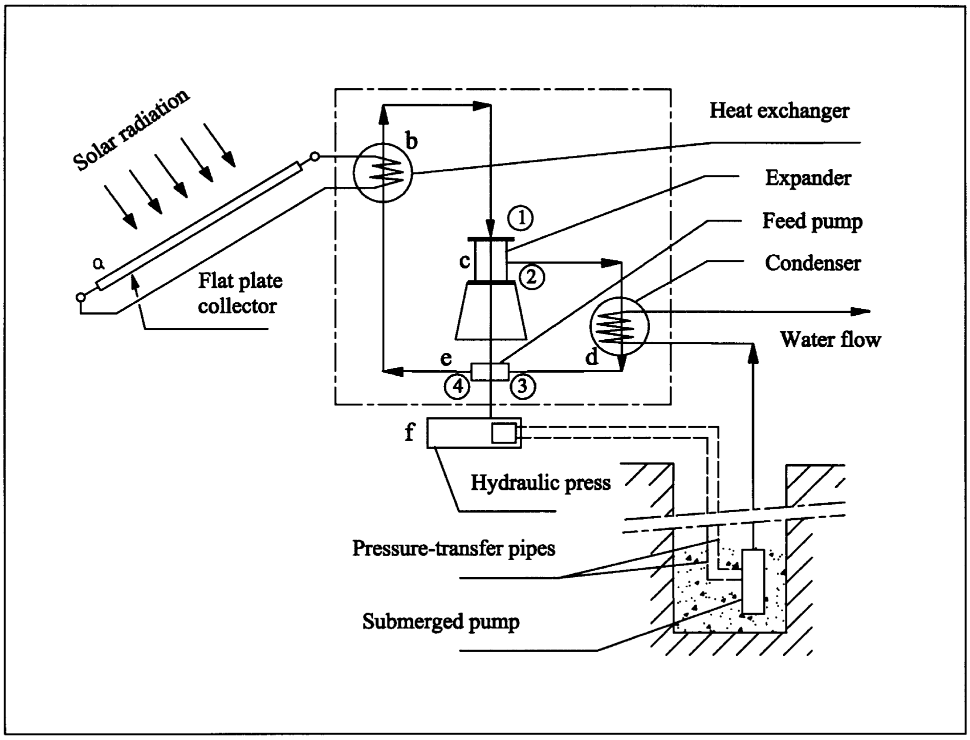

Fig. 7. Schematic diagram of SOFRETES solar water pump.

reciprocating water pump on the other side, the two being connected by a belt drive. The predicted results were compared with observed test data on the installation at Auroville, Pondicherry, India. The experimental results were only 30% of the expected discharge rate and the reasons for this discrepancy have not been mentioned. There were some snags in the installation, particularly with regard to lubrication and the constancy of mechanical efficiency was thus not assured. Also, the system was not optimised.

2.5. *Small installations*

Daniels [17] suggested assemblies of small hot-air solar engines instead of large units and gave arguments in favour of such a system over flat-plate collectors, including higher temperatures, better utilization of winter sunshine, and higher efficiencies. He anticipated low costs for mass-produced small engines of 1/5 kW capacity.

Mathur and Khanna [18] worked on developing high temperature hot air engines operating on an Ericsson cycle. Such a hot air engine developing between 93 and 124 W was used to drive a small water pump which could lift water from a depth of approximately 4.8 m. Parabolic solar concentrators that ran the hot-air engine operated at temperatures ranging from 371 to 649°C.

2.6. *Summary of researchers' experience and recommendations*

- Conventional solar thermal water pumping systems have been attracting attention from users since a standard type of pump can be modified conveniently to be coupled with the vapour generated from a solar collector. No specially designed component is required.
- A flat-plate collector, concentrating collector or solar pond can be employed in a solar thermal water pumping system. However, a concentrating collector or solar pond which is expensive and requires timely maintenance will not be suitable for a village level operation.
- As Sharma and Singh [11] suggested, inexpensive working fluids should be tried in further studies to bring down the present cost of the system. Water seems to be an economical alternative but a concentrating type collector has to be employed to achieve the boiling temperature of water. This increases the overall cost of the system. Therefore, an optimal study has to be done in choosing the working fluid and the collectors to be employed, in order to have the best result with less cost.
- The experimental results of Sharma's pump [11] showed that when discharge head increases, the water pumped per cycle of operation decreases under constant input vapour pressure. Therefore, as Daniel [17] suggested, it is better to have assemblies of small systems instead of a large unit.
- Gupta et al. [16] pointed out some snags in their installation, particularly with regard to lubrication. Severe frictional loss and components damage due to friction involved in any mechanical system remain unsolved problems.
- Amor et al. [19] suggested that solar thermal water pumps should suit local conditions, taking into account not only the required pumping head and climatic

conditions of the locality, but also the pump should meet the following criteria to be of practical use:

—the unit should perform an equivalent amount of work to that of the hand pump which it would most likely replace;

—it should be a low maintenance device having few mechanical moving parts, able to be easily maintained by local unskilled workers and hence fit into a Village Level Operation and Maintenance (VLOM) scheme as set out by the World Bank for similar devices [20];

—the system should rely on appropriate technology to enable local manufacture.

3. Specially designed expanders (unconventional pumps)

Conventional pumping systems are not preferred these days, since not only the capital cost of the system is high, but also the operation and maintenance problems are many because of the number of stages involved in conversion of solar energy to hydraulic work. Therefore, some researchers have focused their attention on inventing simple solar pumping systems which are specially designed and manufactured inexpensively in developing countries without involving any high technology. The installation, operation and maintenance of the solar pumps should be simple as only unskilled manpower is available in rural areas. Also, it would be difficult to have access to any special equipment or parts if required. In order to lower the damage of components due to friction and reduce the demand on frequent maintenance, the pumping system should be designed in such a way that, it functions with few mechanical moving parts.

3.1. *The theory*

In the recent past, several special designs for solar water pumping systems have been studied. Most of these systems have the advantages of being simple, inexpensive, maintenance-free, easily assembled and non-mechanical. These kind of pumping systems have attracted attention from researchers in recent decades. The prime working principles of unconventional pumping systems described by different researchers are based on the same concept. Different modifications are, however, made to satisfy different working conditions and requirements, locally.

In the early 1960, Jenness [21] observed that the required precision and high cost in manufacture of parts, installation and maintenance of pumping systems had made the traditional type of solar powered pumping systems unattractive. No small and inexpensive steam engine of turbine or piston type had been available. Therefore, he introduced a pump called the ‘Savery Pump’ [22] which has no moving parts. The Savery water pump is of interest because of its simplicity which may offset its low operating efficiency. It has no moving parts except some valves which have to operate automatically. Its efficiency is reported to be about 4.5%.

Figure 8 shows the simplified operating cycle of the Savery pump. First, the steam inlet valve and water outlet valve are opened to fill the tank with saturated steam at atmospheric pressure as shown in Fig. 8(a). Next, the steam inlet valve and water outlet valve are closed and the steam cools. This operation causes it to condense and lower the pressure in the tank, opening the water inlet valve (Fig. 8(b)) and drawing water into the tank. The incoming water accelerates the condensation of steam. When the tank is filled with water, the water inlet valve is closed and the steam inlet and water outlet valves are opened, draining out the water and admitting saturated steam to the tank (Fig. 8(c)) after which the cycle is repeated.

Most of the unconventional pumps work on a different principle [23]. The increase in volume on vapourization of a liquid at a temperature far above its critical point is about 50–100 times. If a liquid confined in a closed tank is vapourized, a part of the same can be pumped, as vapourization proceeds, to a higher elevation depending on the saturation pressure. On condensing the vapour at a temperature below its normal boiling point, the liquid can be drawn into the tank from a source close to its level. Thus pumping of the liquid can be carried out.

If water is to be pumped, based on the above principle, a heat source at a temperature higher than 100°C is needed to boil the water. Unfortunately, at the present state of development, such high temperatures are not attainable with an ordinary flat-plate collector at a reasonable efficiency level. However, if a secondary working fluid

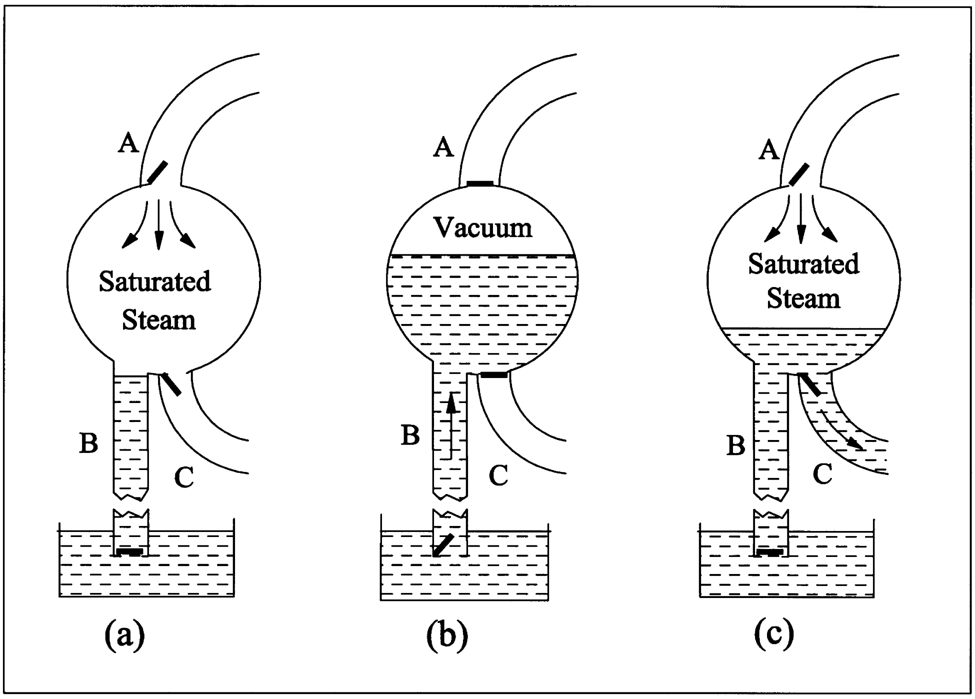

Fig. 8. Operation cycle of the Savery pump.

which is immiscible with water and has a normal boiling point slightly higher than atmospheric temperature, is confined in a closed tank along with water and is vapourized continuously at temperatures attainable with the flat-plate collectors, water can be pumped to a higher elevation. On condensing the vapour, rejecting heat to the surroundings, water can be drawn into the tank from a source which is almost in level with the tank. The working fluid can be pentane or a petroleum fraction having a boiling range of 35–40°C. Recently, many inexpensive pumping systems have been developed based on this 'vapour in, water out' principle.

In general, the unconventional pumping systems can be classified into two kinds based on the mode of condensation of the exhaust vapour, after each cycle of pumping action [23]. In one type, the vapour is condensed at night through the solar collector and is called an 'air cooled pump'. The other type employs water that is being pumped and this is called a 'water cooled pump'.

3.2. *Air-cooled pumps*

In order to vapourize water to steam (>100°C), a concentrating type of collector is required. Figure 9 indicates how a solar powered Savery pump with automatically operated valves function [21]. This system also works on a 'vapour in, water out' basis described previously. Reflector A concentrates solar radiation onto boiler B, in which steam is generated. Having achieved the desired pressure, steam enters tank D through valve E which is raised and opened by float F when water rises to the top of the tank. As the water in tank D gets pumped out through the pipe J, the water level descends to the bottom of the tank, and float G, hanging from the chain, pulls the steam inlet valve shut. When steam condenses, vacuum is created in the tank. The vacuum results in drawing well water up through hose K. Sinking-ball valve L prevents the flow of water back into the well. This Savery steam-powered lift pump has no moving parts except for a few valves, and thereby the maintenance can be largely reduced. Installation of it is possible with only a few simple hand tools. The approximate efficiency of such pumps is about 4.5% with most of its heat being lost through steam condensation.

A heat-driven pump was investigated by Sheldon et al. [24] in 1976. In his work, he made a preliminary study of a hydraulic device which converts heat energy into head to which the water has to be lifted, with no moving parts other than a check valve. The device utilizes oscillations which occur in a heated liquid-vapour column. Originally this device was examined for marine propulsion applications; however, because of the direct method of heating and the simplicity of design and construction, it could be useful as a solar-powered pump in undeveloped areas. With no rotating or sliding seals this pump is well suited for the pumping of a high-purity or highly corrosive liquid. Because of its ability to utilize a low-grade heat source, it might also be considered for use in a waste heat cycle. Schematic of the heat-driven pump is shown in Fig. 10. The apparatus consists of a 4 mm inner diameter glass tube heated externally over 12.5 cm length near the closed upper end. The tube is initially completely filled with water which begins to vapourize as the tube is heated. Eventually, the vapour cavity extends below the heated region. Oscillation begins when some

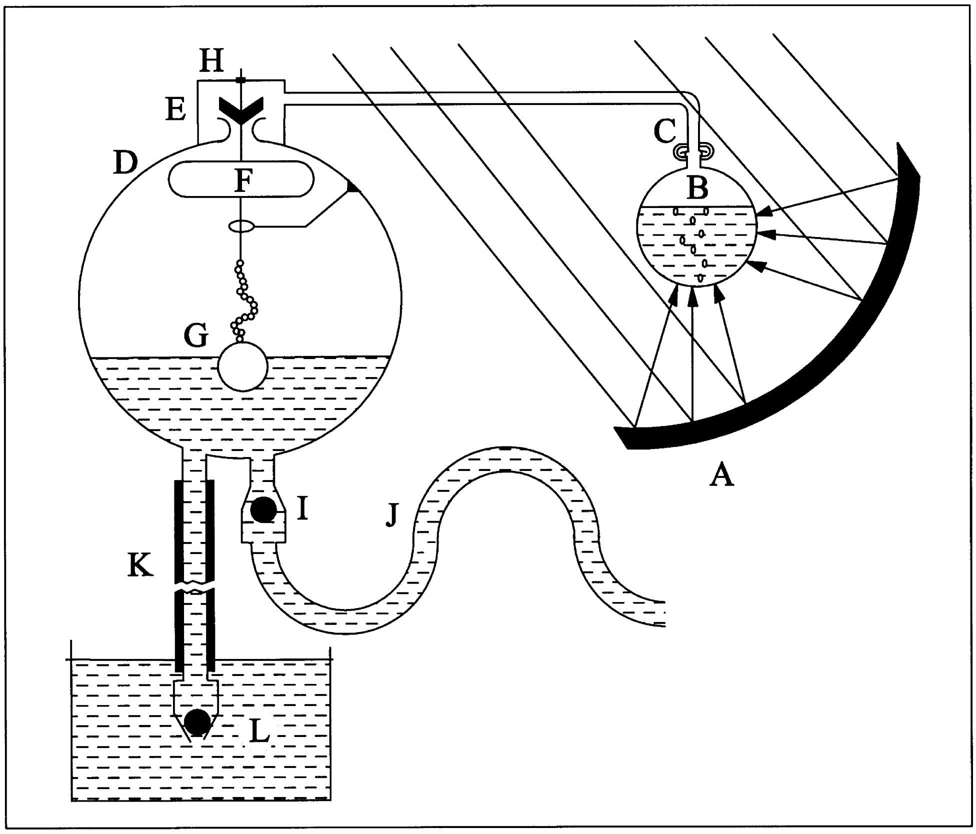

Fig. 9. Automatic solar-powered Savery pump.

of the vapour condenses; the column moves up into the heated region, vapourization reoccurs, the liquid column again is forced down and the cycle repeats. The lower end of the column opens into a reservoir at atmospheric pressure. Just above this reservoir a suction line and check valve join the main column. Water is drawn through the check valve from the lower reservoir due to the fluid motion in the main tube. This water is then discharged into the upper reservoir. The measured water column displacement varies from cycle to cycle with a range from 2.5 to 5 cm and increases with additional cooling. The volumetric displacement of the liquid column is about 6 ml s^{-1}; volumetric efficiencies of 43 and 11% were obtained for 2.5 and 36 cm heads, respectively.

Fluidyne systems have been popular in the early 1980s. Mankbadi [5] reported that the Gedeon's system produced an overall efficiency of around 3%. These results have made the system very attractive since it obtains reasonable efficiency, and, at the same time, requires extremely simple technology and no mechanical moving parts. A sketch of this Fluidyne system is shown in Fig. 11.

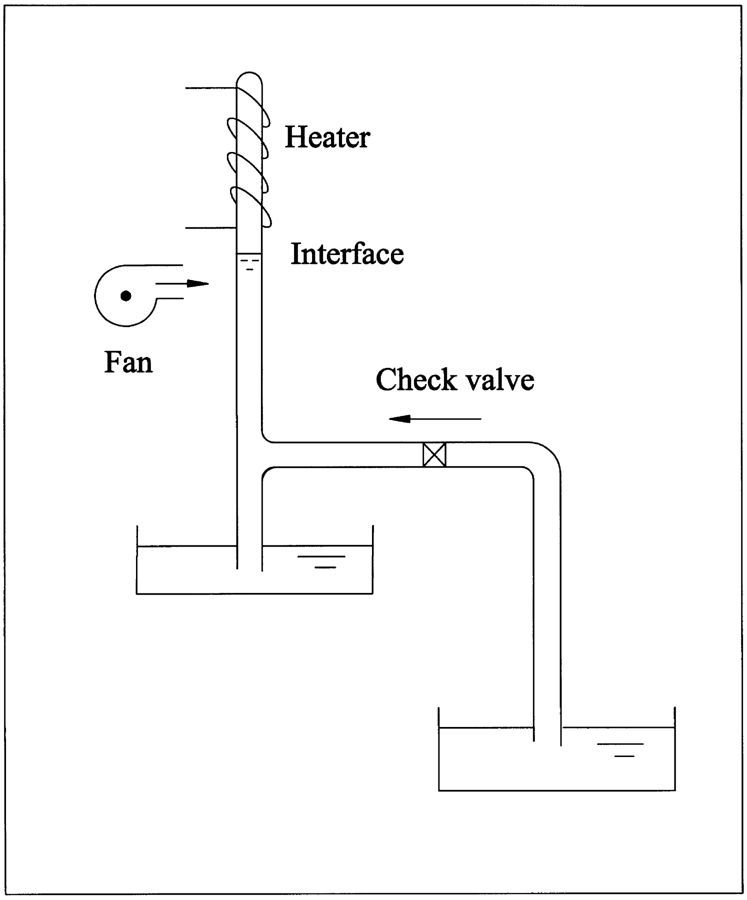

Fig. 10. Heat-driven pump.

Muralidhar [1], in his review paper, referred to an interesting fluidyne pump developed at Harwell, England. The pump is a very simple machine having no moving parts except a couple of valves. It needs no seals, no lubrication and requires practically no attention. It can run on solar energy or waste heat. The pump operates on the principle of liquid piston engine. The water column in a U-tube acts as a piston pushing the trapped air back and forth between the hot zone and the cold zone. A part of the heat is thus converted into work to pump the water. This pump could lift a gallon of water per minute through a 1 m pumping head. The efficiency was claimed to be low but the simple design of it is attractive.

Rao and Rao [23] worked on a solar water pump for lift irrigation, which employed few displacement tanks to effect pumping. Schematic of the water pump is shown in Fig. 12. The pump worked on the similar principle as explained earlier. That is, the volume increase at a given pressure is utilized to displace water to a higher level and

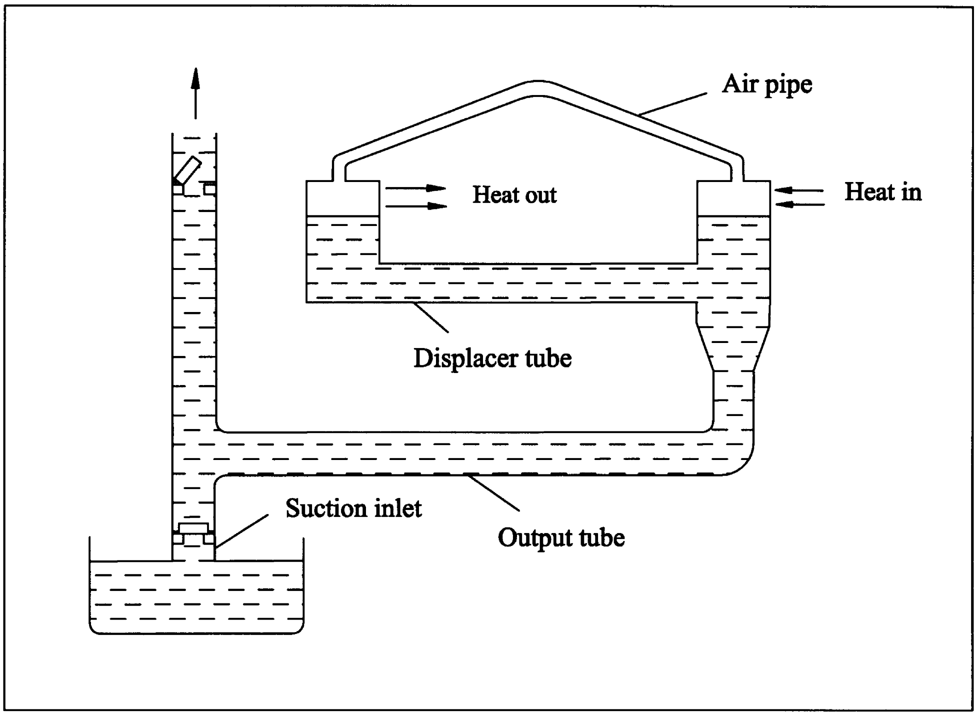

Fig. 11. Fluidyne pump.

the volume reduction at a lower pressure is used for suction of water from a depth. The volume of water displaced is equal to the change in the volume of the fluid undergoing phase change. The thermodynamic analysis of the cycle and design aspects have been discussed by Rao and Rao [23]. The pump has no moving parts except for check valves. Neither an auxiliary power source nor high technical skill is required to operate the pump. The system operates with commercial pentane. Pentane is vaporised in flat-plate collectors under pressure. The pentane vapour is allowed to pressurise water in a closed tank, immersed in the well water, effecting pumping of water to a higher elevation. On condensation of the vapour, a partial vacuum is created and water is drawn into the tank. Two types of pumps are discussed. In the air cooled pump, the vapour is condensed at night through the solar collectors. The details of the water cooled pump will be explained in the next section. Table 1 gives the energy requirements of an air cooled pump.

Bhide [25] refers to the experimental observations on a French solar water pump developed by Ican Pierre, a French engineer, the reported efficiency of which was of the order of 1%. Water was heated in a 12 m^2 solar collector. The heated water evaporated a volatile liquid (methyl chloride). Expanding methyl chloride vapour did work on the piston driving the hydraulic pump. It is reported that the pump could lift 1200 l of water to a discharge head of 15 m.

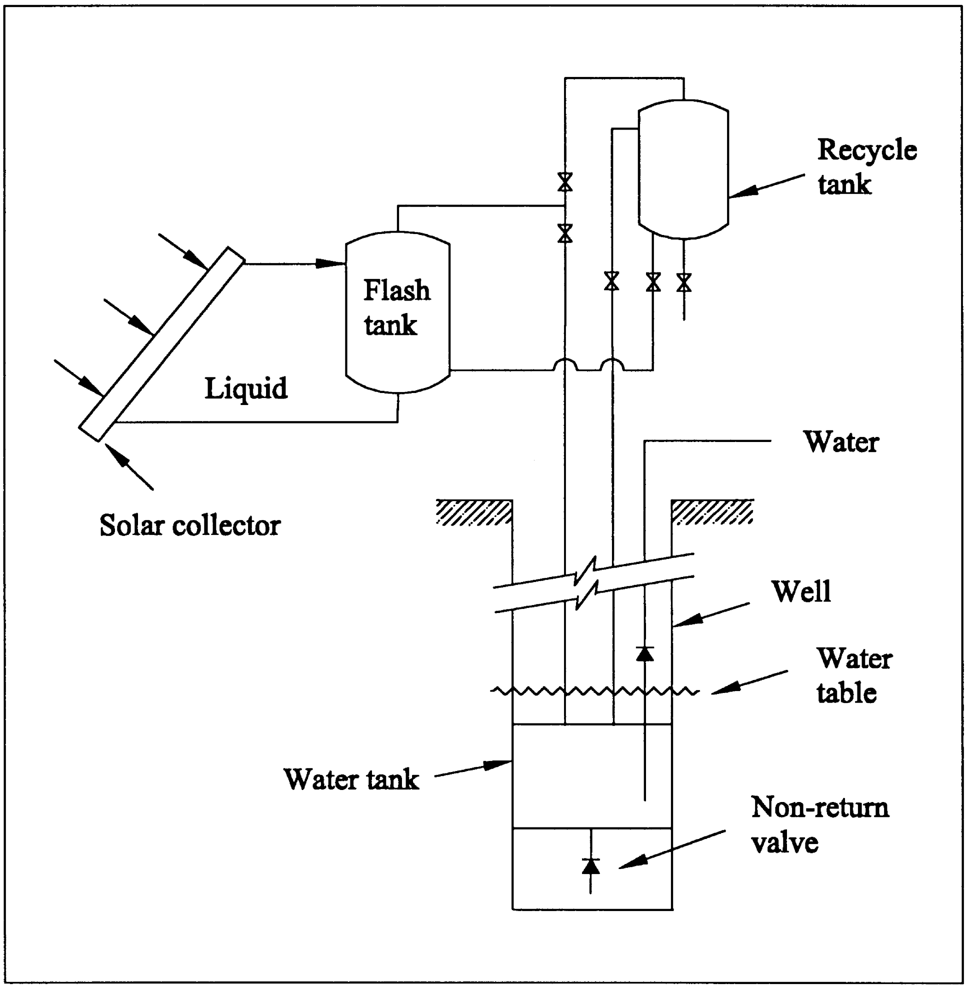

Fig. 12. Sketch of air-cooled pump.

Soin et al. [26] have studied the performance of an air cooled solar water pump with a capacity of 2600 l per day over an operating period of 7 months. The experimental results and the operational problems are discussed. They also discuss the operational problems of a 120,000 l per day, 12 m lift, water cooled pump, besides discussing the design of a 'direct cooled pump'.

3.3. *Water-cooled pumps*

The daily pumping capacity is limited by the water tank size as described by Rao and Rao [23]. The exhaust vapour, after pumping the water from the well, can be cooled and condensed at night. The collector acts as a condenser for the working

Table 1
Energy requirement of air-cooled pump

Net lift of water [m]	9.14	18.29	27.43
Collector temperature [°C]	62.2	74.4	83.9
Collector area [m^2]	23.2	37.2	51.1
Energy to preheat pentane and flash tank [kJ]	55,849	100,949	136,257
Theoretical energy requirement [kJ]	59,884	74,106	94,097
Heat losses to			
(a) side wall [kJ]	139,907	204,000	206,853
(b) top cover [kJ]	16,022	20,985	23,064
(c) to pentane layer on water [kJ]	40,393	52,910	58,144
Preheating period	07:00 h	07:00 h	07:00 h
	10:00 h	10:00 h	10:00 h
Pumping period	10:00 h	10:00 h	10:00 h
	15:00 h	15:00 h	15:00 h

Tank size: diameter 3.05 m, height 3.66 m, effective volume: 24.92 m^3

fluid, rejecting heat to ambient by convection and radiation. For lift irrigation of a meaningful quantum of land, the volume of the water tank may be too high to be economical. This limitation could be positively overcome by using water as the heat-transfer fluid to condense the spent vapour. Therefore, these water-cooled pumps are proved to be efficient in comparison to air-cooled pumps in terms of the quantity of water lifted per day.

Maccracken [27] and Bold [28] worked on water-cooled solar thermal water pumps which had a U-tube to facilitate condensation. The schematic of the 'Maccracken thermopump' is shown in Fig. 13. The pump operates on the same principle (volume change basis) as explained earlier. As heat, from a solar collector, is supplied to the generator, the liquid evaporates, changes volume, pushes the floater down and discharges the water in the collapsible rubber lung from the top. When the floater reaches the bottom of its stroke, the vapour escapes through the vapour tube and is condensed when it comes in contact with the liquid, which has been cooled by the cold water in the rubber lung. When all the vapour is condensed, the pressure is decreased, water is lifted from the reservoir, the floater moves up to block the entrance to the vapour tube, and liquid fills both the cylinder and the generator, and the intermittent pumping action starts again. A suitable working medium, e.g. R-11, may be used for this thermopump to operate with a solar collector in order to pump water to a desired elevation, and when cooled by the wall, create a suction to lift water from a certain depth.

A thermal actuated pump was developed on a laboratory scale by El-Mallah and Mohamad [29] and proved to be quite reliable. The working principle is similar to the Maccracken thermopump [27]. The operation of the pump can be explained by reference to Fig. 14. Firstly, the pump has to be filled completely with water. As the heat source is applied to the pump, steam is produced and water then flows from the pump cylinder to the outlet pipe through the condenser tube. As soon as the water surface in the pump cylinder reaches the bottom of the U-tube, a hydraulic instability

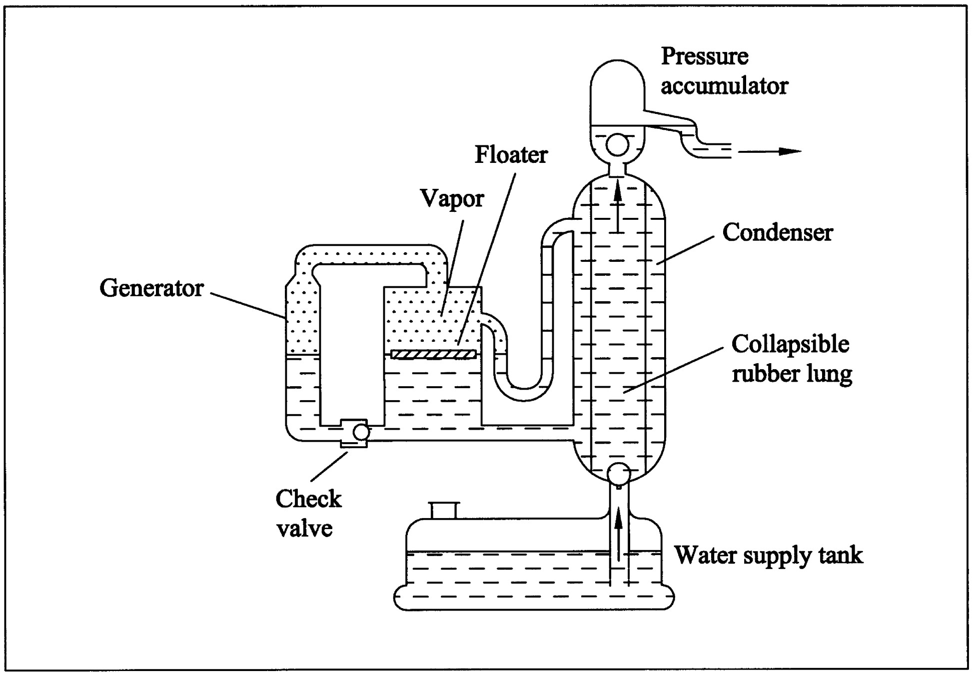

Fig. 13. Maccracken's thermopump.

occurs and triggering action takes place making a syphon action and the steam in the pump cylinder will be sucked into the condenser. As the steam is condensed, vacuum is created in the pump and a suction stroke takes place to fill the pump with water from the source, and a new cycle starts.

The design of the preceding listed water-cooled pumps are suitable only for shallow water sources. However, the nature of irrigation in an arid region calls for a pumping system which is capable of lifting water from deep wells.

Bhattacharyya et al. [30] describe a bellows-actuated solar pump having no moving parts (Fig. 15). Thermodynamic analysis, relevant numerical results and limited experimental data on a trial unit of fractional horsepower are presented. Simplicity of design, reasonable efficiency and ease in multi-staging for large heads are supposed to be its main advantages. Energy collected in flat-plate collectors runs a Rankine cycle operating with a low temperature boiling liquid. The working fluid circuit is a closed one and is separated from water being pumped so that the latter remains uncontaminated. The system consists of an array of flat-plate collectors, a boiler drum, bellow chamber, water chamber and a condenser cooled by the pumped water. The flexible bellows in the bellows chamber forms the critical part of the system. In principle, the solar heat collected by the collector array is utilized to boil the working liquid that is contained in the collector tube grids and partly in the boiler drum. The generated vapour is accumulated and its pressure rises according to its temperature.

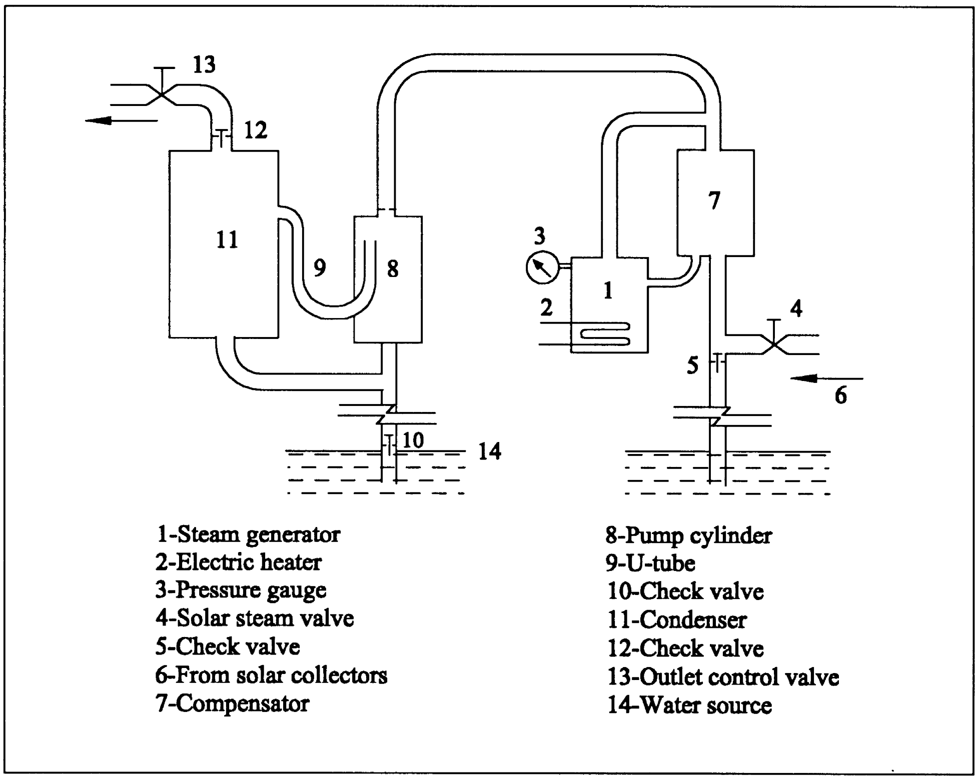

Fig. 14. El-Mallah and Mohamad's U-tube pump [29].

Having obtained the desired pressure in the boiler drum, the bellows in the bellows chamber is alternatively connected to the vapour chamber and condenser by means of a three-way valve. This causes the bellows to expand and contract in the confined actuating water chamber, which is initially filled with water. The latter has suction and delivery pipelines with check valves. The suction line drops in the water supply reservoir. The expansion and contraction of the bellows causes, respectively, pressurization and rarification of the trapped air in the bellows chamber which, in turn, acts on the water in the water chamber to effect alternately delivery and suction of water. After many cycles of operation, the condensate is returned to the vapour chamber by equalizing the pressures in the vapour chamber and in the condenser. The overall efficiency of the pump is 1–2% at an average pumping rate of 900 $l\,h^{-1}$. Simplicity of design, reasonable efficiency and ease in multi-staging for large heads are the main advantages attributed to this type of solar pump.

Diaphragms can also be used to aid pumping of water from a well, instead of a bellows. Murphy [31, 32] developed a system similar to that of Bhattacharyya et al. [30]. This is illustrated schematically in Fig. 16. This system is a more compact one campared to a bellows actuated pump, and was called 'Solar Liquid Piston Pump'. It

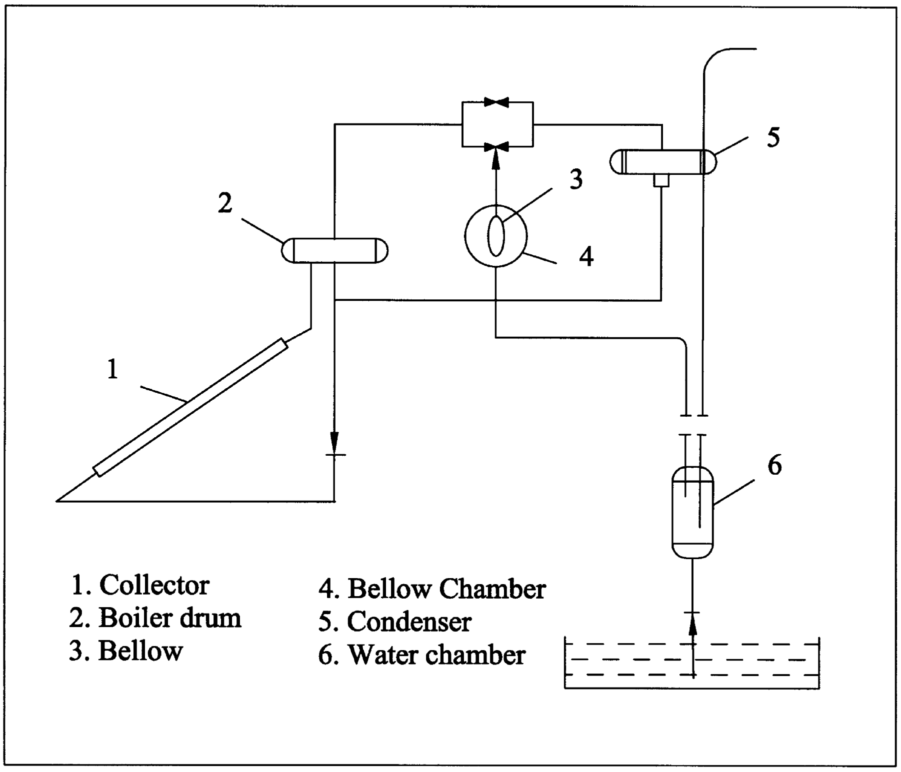

Fig. 15. Bellow actuated solar water pump.

has the characteristic feature of liquid piston pumps, namely the up and down oscillation of a liquid column; this oscillation induces suction and delivery of water through one-way valves located in the inlet and outlet pipes. The main components of the SLPP are pump cylinder, evaporator, condenser, two one-way valve and an appropriate working fluid, in this case Freon 113, which is separated from the pumped water by a diaphragm. Hot water at approximately 80°C flows through the evaporator. As evaporation proceeds, the vapour downloads until it falls below the evaporator and evaporation ceases. In the absence of evaporation (i.e. when the liquid column is below the evaporator) freon vapour is condensed by cooling water which circulates through the condenser, and the vapour pressure in the pump cylinder drops. The low pressure sucks the liquid column upward until contact is re-established with the evaporator. A heat source and sink are required for pump operation. In a field installation, hot water would be generated in a solar water heater and delivered by natural circulation while cooling water is bled off from the pumped water.

A locally-designed SLPP prototype, 750 mm tall with a diameter of 112 mm, was constructed using plexiglass and mild steel tubes for the main pump cylinder and copper tubing (coils) for the evaporator and condenser. The prototype was tested in

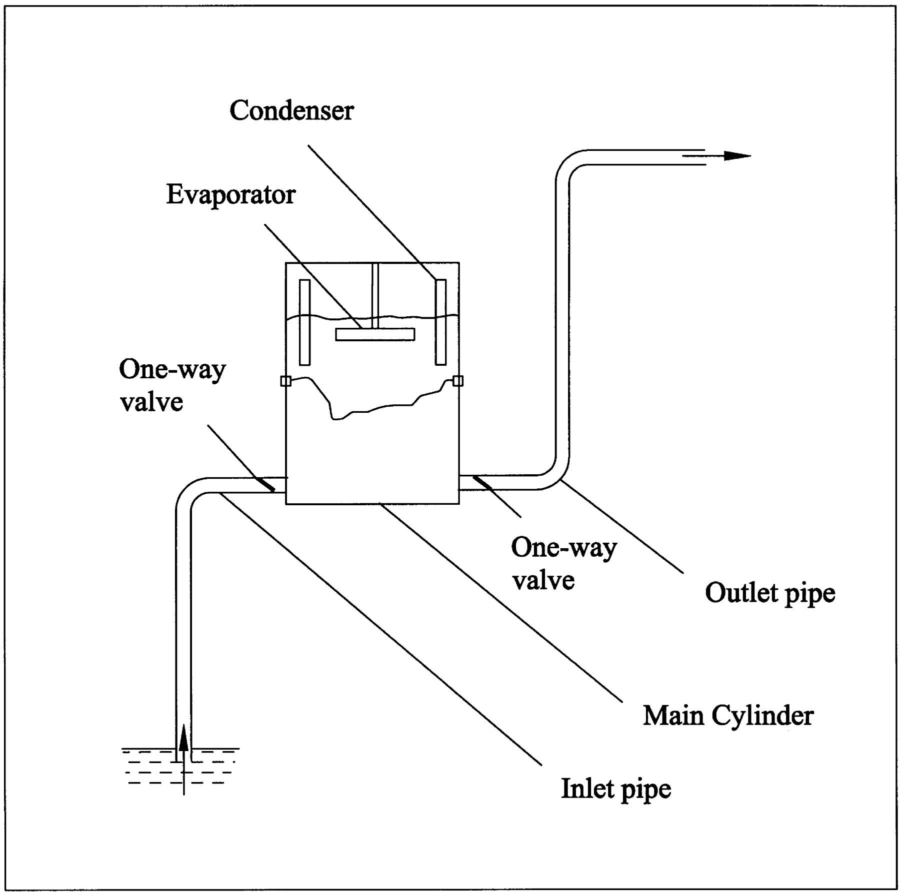

Fig. 16. Solar liquid piston pumping system.

the laboratory. The maximum pump head attained by the prototype was 0.8 m with a corresponding discharge of 0.15 l s^{-1}. The discharge rates fall within the same range but the pump heads obtained with the SLPP prototype are much less than those obtained in other unconventional pumps.

The bellows and the diaphragm water pumping systems have the advantages of being simple, cheap, and reliable. They are also reasonably efficient. Also, the bellows, diaphragm, or any other end-plate provided reciprocating pump prevents the mixing up of the working fluid and the water being pumped. This avoids the contamination of the water to be pumped whose end use is either irrigation or potable water. However, regular replacement of the diaphragm and the bellows will be required as repeated stresses cause serious fatigue, which may increase the maintenance cost of such pumps.

The Brown-Boveri system (Fig. 17), referred by Mankbadi [5], is a similar system except for the absence of the diaphragm. Since there is no diaphragm or a float in the system, the working fluid is absorbed by the water and the water to be pumped is contaminated. It may turn out to be hazardous for irrigation farms. Also, such pumps can not be employed where pumped water is used for drinking purposes. There is a possibility of contamination of water with the working fluid.

From the preceding examples [30–32], it is clear that the use of a diaphragm or a bellow in the system should be designed in such a way as to avoid miscibility of the working fluid with the water to be pumped, as explained by Murphy [31, 32].

To avoid direct contact of the working fluid and the water to be pumped, Venkatesh [33] added a few additional tanks, A and B, to the Brown-Boveri system design between the separation tank (previously called the flash tank) and the well tank (previously called the expansion chamber). The working of the solar thermal water pump is briefly described here with the help of the schematic diagram in Fig. 18. Liquid pentane is heated in the collector, by a thermosiphon flow. When the pressure

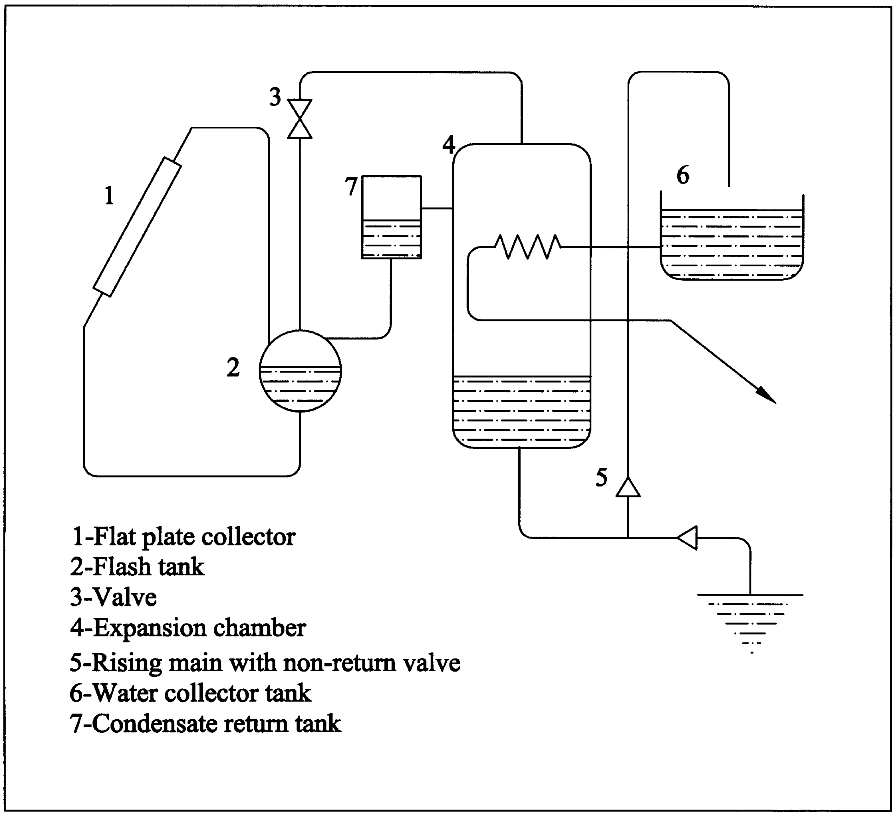

Fig. 17. Brown Boveri system.

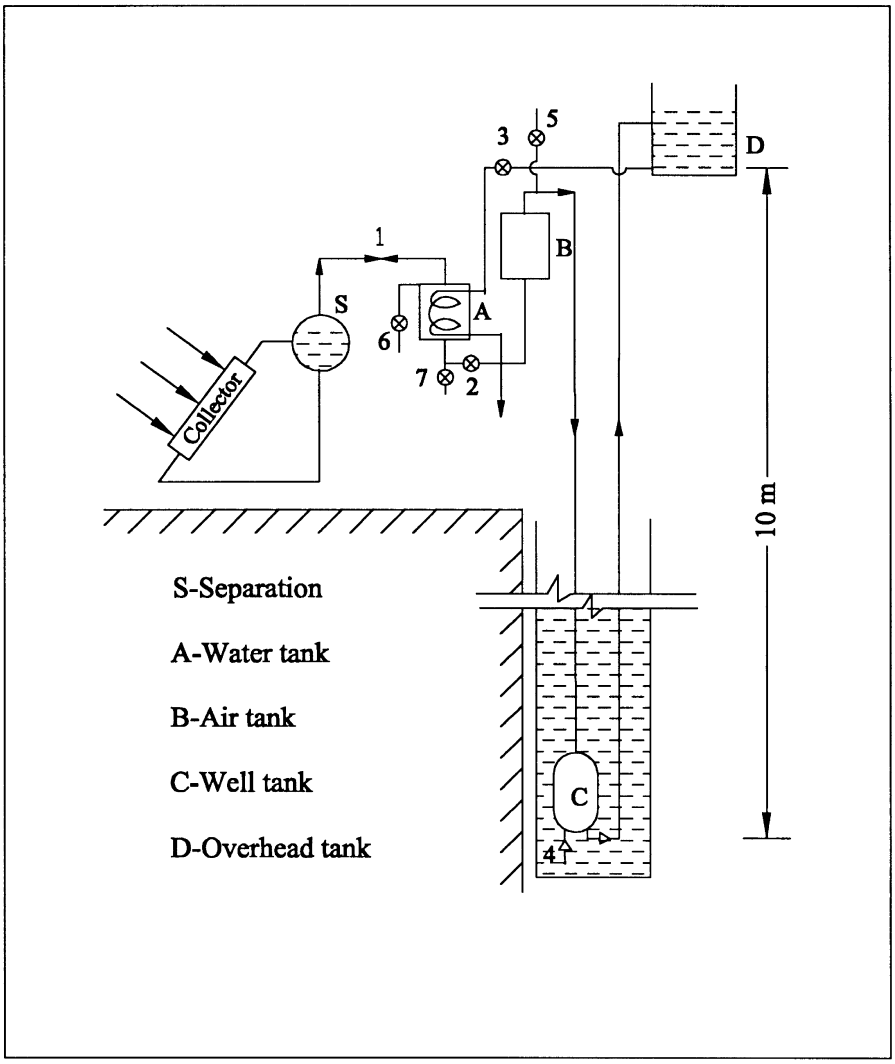

Fig. 18. Schematic of the pumping system.

in tank S reaches a predetermined value the vapour from tanks S is quickly allowed to pass into tank A which contains water. The water in tank A, in turn gets displaced to tank B, which initially contains air at atmospheric conditions. Water entering vessel B compresses the air in it to the discharge pressure. This compressed air pushes the water from vessel C (which is immersed in well water) to the overhead tank D. At the end of this pumping, water in the overhead tank D is allowed to pass through the cooling coils in vessel A on way to the end use of the pumped water. The water flowing through the cooling coil accelerates the condensation of pentane vapour in

vessel A. Because of this condensation, pressure in vessel A decreases. This reduction in pressure causes water in vessel B to return to vessel A, thereby bringing the water in vessel C, through the one way valve 4. The system is now ready for the next cycle.

The pressure of pentane vapour in tank S at the start of any cycle is either greater than or equal to its pressure at the start of the previous cycle. Between any two cycles, the pressure of pentane in the collector system decreases when S communicates with A. Hence, it takes some time to restore the pressure to its initial state. If this period, referred to as the 'heating time', is less than the 'condensation time' (time taken for pentane vapour in A to condense completely), the temperature and thus the pressure in the collector system will be higher at the start of the next cycle. This is because the next cycle cannot be started until and unless the condensation is complete and the collector heats the pentane for a longer period than required.

Kwant et al. [34] have also studied the performance of a solar water pump that uses displacement tanks as shown in Fig. 19. Besides discussing operational problems possible suggestions are made by them to achieve a pump efficiency of 2% with a 10 m^2 single glazed flat-plate collector.

Sudhakar et al. [35] have suggested a modified pump (Fig. 20) based on the theoretical studies of their earlier work [23]. This modified version is suggested to eliminate the direct contact between the working fluid and the water. Thermodynamic analysis has been made to ascertain the advantages of coupling concentrating col-

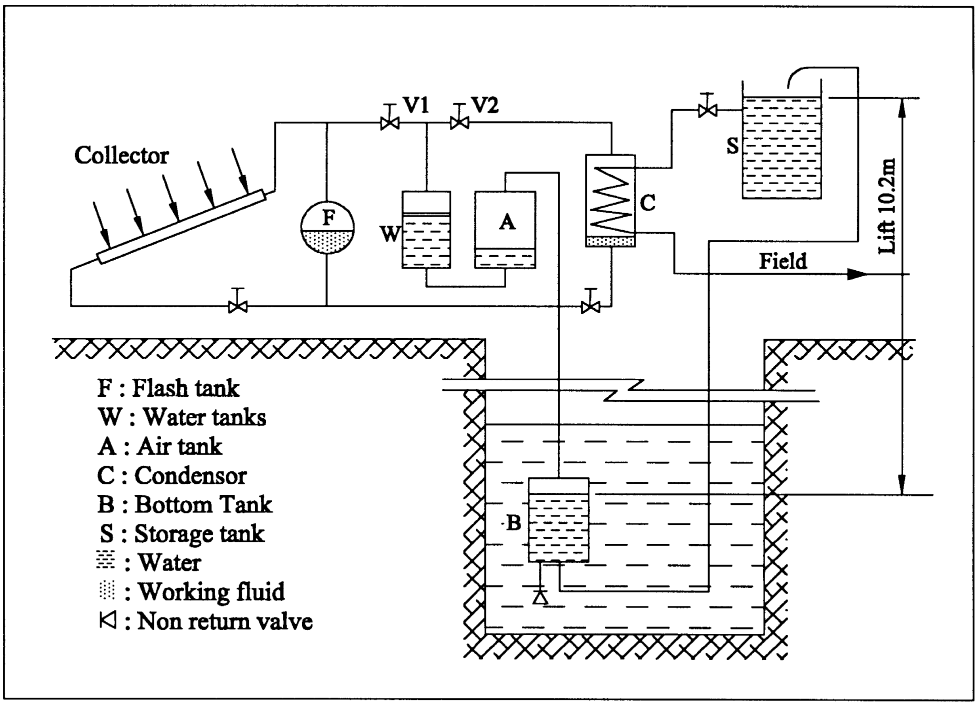

Fig. 19. Diagram of the Kwant et al. [34] pumping system.

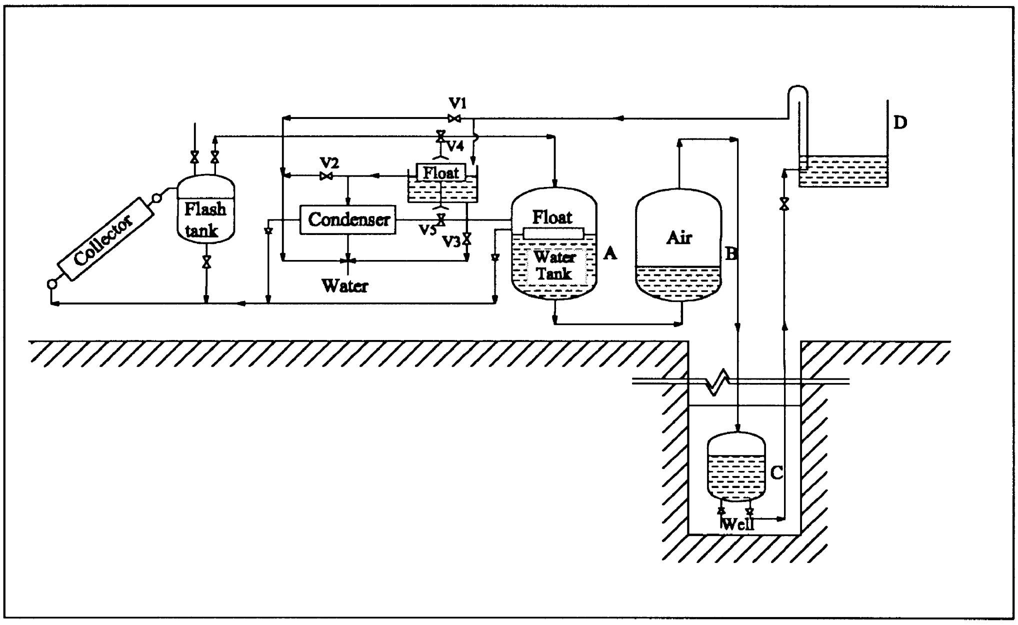

Fig. 20. Sketch of the modified pump.

lectors with the pumping system. To minimise the heat losses in the water tank an internal insulation has been proposed. The performances of the unit with and without internal insulation have been compared. It is reported that a unit employing automatically operated valves with a collection area of 93 m^2 could pump 800,000 l of water per day against a discharge head of 9.1 m.

Sudhakar and Rao [36] have presented an algorithm to simulate the performance of a solar water pump. A pump having a solar collector area of 93 m^2 developed 1.84–2.76 kW, averaged over a period of 6 h per day, depending upon the discharge head. The economic feasibility of the pump for different crop patterns has been studied and it has been shown that the pump is economically viable for heads up to 27.4 m. The studies indicate that the pump is not competitive with diesel and electrical pumps, at present. However, considering the real cost of electrification of a village located 5 km from main transmission lines, the solar pump is economical compared to the electrical pump.

Hariprakash [37] has worked on a similar pump and reported that its theoretical efficiency is around 0.11–0.13%. A small unit with flat-plate solar collectors of 3 m^2 exposed area, with *n*-pentane as the working substance was tested and the pump could achieve an average overall efficiency of 0.05%.

A laboratory model of a solar pump has been developed and tested by Agarwal and Shreepal [38]. The pump operates on a Rankine cycle with methyl alcohol as the working substance. Superheated methyl alcohol vapour generated in a stationary

Winston collector, with an absorber area of 2.25 m^2, is directed to the pumping section where it pushes a liquid piston of turpentine in a working cylinder. This directly forces water from an L-shaped pipe, connected to the cylinder to rise in a delivery pipe. The vapour, when exhausted to a condenser, produces a partial vacuum in the cylinder causing suction of water from a deep water source. The condensate is taken back to the evaporator and the cycle continues. It is reported that the laboratory model required improvement with regard to automation and increase in efficiency.

Information gathered from the literature reveals that the performance of various pumps, especially the unconventional types with no moving parts, varies over a wide range. Most of the work is experimental in nature under widely varying conditions. A comprehensive theoretical analysis to assess the performance of such types of pumps is lacking.

In view of the above observations, an unconventional pump of the type considered by researchers [23, 34, 35, 37] is selected for detailed analysis, the reason being the pump can be coupled to a flat-plate collector which is fairly inexpensive and rugged; also it is easy to maintain.

In theoretical studies [23, 34, 35] the following assumptions have been made: (1) the intensity of solar radiation on the collector is steady in each cycle; (2) the working substance is always at the saturated temperature corresponding to the given discharge pressure; (3) the collection system always contains a fixed mass of pentane; (4) pentane undergoes a thermodynamic cycle. In these studies, the condensation time needed in the analysis is determined from experiments.

Assumptions (1) and (2) are not correct. The intensity of solar radiation increases with time until noon and decreases thereafter. The temperature of pentane in the collection system cannot be held steady. It keeps on increasing with time as it is heated continuously by solar energy. Contrary to assumption (3), in reality the mass of pentane in the collection system decreases from cycle to cycle as its vapour is taken out of the collection system in each cycle and there is no way it can be immediately fed back to the collector under pressure. Also, assumption (4) that pentane undergoes a thermodynamic cycle is not correct. Strictly speaking the pentane does not undergo a thermodynamic cycle. It is not possible to return the condensed pentane to the collection system, since at any instant the pressure in the collection system is higher than that in the condensing vessel. While analysing the performance of the pump theoretically, the condensation time per cycle should also be predicted.

The facts mentioned above have been taken into consideration to some extent by Hariprakash [37] in his work on solar water pumps. Focusing points were observed in his analysis. (1) He has considered only sensible heating of pentane, in determining its temperature rise at any instant. (2) In balancing the energy equation he has not considered the net heat capacity of the collection system. (3) He has also not considered the losses from the collection system, which have a profound effect on the temperature of pentane in the system. (4) Theoretically, he has assumed that the pump starts operating as soon as the system reaches a pressure equal to the discharge head. (5) The actual mass of pentane required per cycle was more than the predicted one. (6) The pressure/ temperature in the collection system were very high when the pump was not operating, which constitutes a loss of potential. (7) The vessel sizes were not

in correct proportion to make use of the vapour generated in an effective way. (8) There was a large difference between predicted and measured values. (9) The overall efficiency reported was very low.

An attempt was made by Sumathy et al. [39–41] to perform a complete analysis of a solar thermal water pumping system which includes collector analysis [39], analysis of the condenser [40] and the thermodynamic analysis of the pump [41]. The system under analysis is shown in Fig. 21. The increase in temperature of the working fluid,

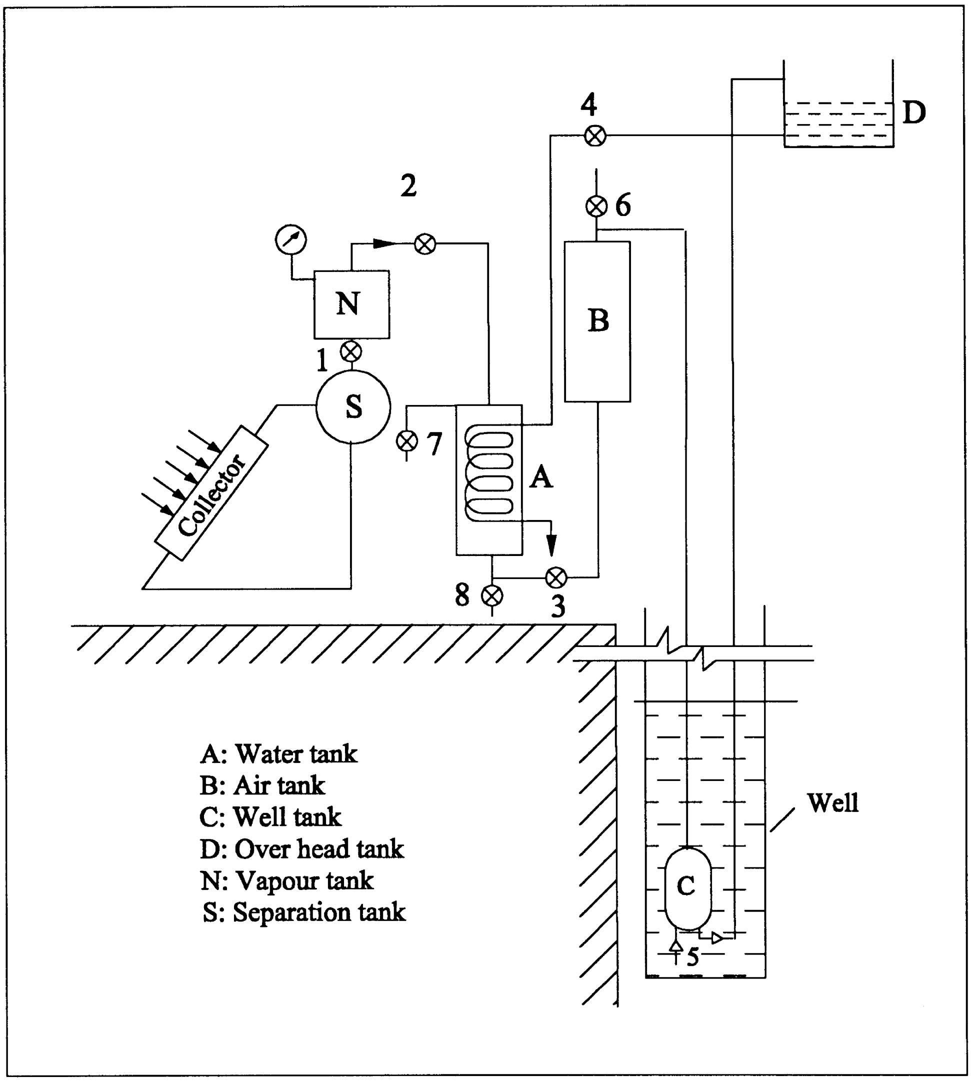

Fig. 21. Schematic of the Sumathy et al. [39–41] solar thermal water pump.

pentane, was predicted, treating pentane being heated as a mixture of liquid and vapour. It was shown in the study that limiting the pressure and temperature of pentane during heating, by using a vapour storage tank N, improved the performance of the pump. In the absence of the vapour storage tank, when liquid pentane at a higher pressure in the collector communicates with vessel A, the pentane vapour gushes into the latter. The pentane vapour suddenly rushing into vessel A also entrains some liquid pentane along with it. This results in the increase of mass of pentane required in each cycle leading to reduced efficiency and other associated problems.

The thermodynamic analysis in conjunction with the heat-transfer analysis of the collector predicts the performance of this modified pump (Fig. 21) having an additional vapour storage tank. For an assumed set of parameters, such as the pattern of intensity of solar radiation, collector characteristics, meteorological data, the mass of pentane initially in the system and the discharge head, the heating time, the condensation time per cycle, the number of cycles per day, the mass of water lifted per day and the overall efficiency were evaluated from the thermodynamic analysis. The predicted results were discussed and compared with experimental data.

The overall efficiency of the pump is small. This is because of the fact that there are a number of stages of conversion of solar energy to hydraulic work. The system using a non-selectively coated flat-plate collector, whose efficiency especially at high temperatures, is known to be low of the order of 20–30%. Also, most of the energy is used in heating the large quantity of liquid first, to the required pressure. The efficiency of the pump realized experimentally is comparable to the efficiency values reported by Hariparkash [37] and Kwant et al. [34]. Working on similar units with a large number of flat-plate collectors, they have reported experimental efficiencies of 0.08 and 0.1% respectively at the discharge head of 10 m. The corresponding efficiency in this work is 0.12%, which may at best be considered marginally superior.

4. Further studies

4.1. *Reasons for the low efficiency of the pump*

Low efficiencies of devices operating on flat-plate collectors are too well known. However, in this case, the efficiency is rather very low. This necessitates a careful investigation.

- The manner in which the pentane vapour displaces water in vessel A, requires a careful review. Since the rate of vapour generation through flat-plate collectors is low for obvious reasons, the water can only be displaced slowly by this vapour. Slow displacement causes condensation of some amount of vapour during the pumping process. This requires more pentane to do the job than the estimated quantity. To improve the performance, it is essential that the pentane vapour displaces water as quickly as possible.

- In the experimental work of the other researchers [28, 37], the flat-plate collectors are operating at unnecessarily high temperatures beyond 10:30 h. This reduces the collection efficiency and thus the overall efficiency of the pump.
- The exposed area of the collector is not optimized in the work of the other researchers.
- The pump was out of action for a small period of few minutes at an interval of every 5–6 cycles to remove the liquid pentane from vessel A. During this period the heating in the collector was continued resulting in greater losses from the collector.
- The pumping process was not instantaneous. Also, there are too many valves to be controlled manually, which results in reduced efficiency.

4.2. *Recommendations*

- The disadvantage associated with the slow displacement of water by vapour can only be eliminated by resorting to instantaneous filling. This could be achieved by having a storage tank, where the vapour could be collected at the required pressure to be used as and when required. This avoids the condensation of vapour in vessel A during the process of pumping the water.
- When the collector reaches the minimum pressure required to operate the pump there is no need to further heat the pentane in the collectors. From this instant onwards, as and when the pentane vapour is used for pumping water, the collector must be able to replenish this vapour by making use of solar energy to supply only the required enthalpy of vapourization. However, the amount of pentane vapour used by the pump in each cycle is much less than the generating capacity of the collectors. This causes the pentane in the collectors to be unnecessarily heated to very high temperatures at the cost of efficiency. This problem can only be eliminated by proper optimization of the volumes of vessels A, B and C and the collector supplies only that mass of pentane vapour which the vessels A, B, and C can handle in each cycle. If this is not possible one or more parallel pumpings can be done using the vapour generated by the collectors.
- Vessel A has to be insulated well. It is also advisable to have an insulating float in the vessel, to reduce the problem of condensation of pentane vapour during the period of pumping.
- It is preferred to have condensation in a separated chamber, so that the pump can be operated continuously without any stopping for removal of condensed pentane from vessel A.
- Changing the working fluid in the solar collector in such a way that the new working fluid has a vapour pressure of 2 abs. bar at the same temperature at which the pentane has 1 abs. bar, (e.g. using a suitable mixture of isopentane and butane) the temperature swing of the vapour in vessel A necessary for producing a pressure swing of 1 bar would be smaller; however the amount of vapour to be condensed in reservoir A at each cycle would remain the same, as it always corresponds to a partial pressure of 1 bar. (On the other side will be increased the small amount of heat to be extracted as sensible heat for cooling the remaining vapour.)

- A float-valve has been recently upgraded [42] for use with low-density fluids, just like pentane. Combining the float-valve with the water pumping system, it is possible to conceive a device making the same job, but working in an automatic way.

5. Conclusions

The development of solar thermal water pumps for irrigation is promising. The technology continues to develop, and the cost of producing power with solar thermal water pumps is falling. If the costs of fossil fuels, transportation, energy conversion, electricity transmission and system maintenance are taken into account, the cost of energy produced by solar thermal water pumps would be much lower than that for electrical water pumps.

Of two main kinds of solar thermal water pumping systems discussed in this paper, the unconventional types are relatively simple and non-mechanical. Their installation and maintenance can be carried out by untrained workers. In spite of low efficiency, these pumps are attractive to users since solar energy is abundantly available. Also, most of the solar thermal water pumps will probably be located in the farming village, where land is relatively inexpensive and water demand goes along with the solar radiation available, rather than for commercial use owing to their bulk and relatively low pumping head. Further research to overcome these limitations is essential if systems are to be adopted for commercial usage in future. Any method that improves the efficiency even marginally would be a long way in improving the economics of operating such devices.

References

[1] Murlidhar HP. A review of solar pumps and their principles. Proceedings of the International Solar Energy Society Congress, New Delhi, India, 1978, pp. 2129–33.
[2] Bahadori MN. Solar water pumping. Solar Energy 1978;21:307–16.
[3] Roger Hsiao Y, Blevins BA. Direct coupling of photovoltaic power source to water pumping system. Solar Energy 1984;32(4):489–98.
[4] Pytlinski JT. Solar energy installations for pumping irrigation water. Solar Energy 1978;21:255–62.
[5] Mankbadi RR, Ayad SS. Small-scale solar pumping: the technology. Energy Conversion and Management 1988;28(2):171–84.
[6] Tabor H, Bronicki L. Small turbine for solar energy power package. Paper 35/S/54 UN Conference on New Sources of Energy, Rome, 1961.
[7] Talbert SG, Fischer RD, Alexander G. The development of a 37 kW solar-powered irrigation system. Proceedings of the International Solar Energy Society Congress, New Delhi, India, 1978, pp. 2138–42.
[8] Farber EA, Prescott FL. Closed-cycle solar hot-air engines—part 1, a 1/4 h.p. engine. Solar Energy 1965;9(4):170–76.
[9] Tellier C, Paris. Patenschrift No. 34749. Einrichtung Zur Bethatigung einer Pamprorrichtung Durech Die Sonnenwarme, 1885.
[10] Burton R. A solar powered diaphragm pump. Solar Energy 1983;31(5):523–25.
[11] Sharma MP, Singh G. A low lift solar water pump. Solar Energy 1980;25:273–78.
[12] Leo BS, Hsu ST. A simple reaction turbine as a solar engine. Solar Energy 1960;4(2):16–20.

[13] Farber EA, Prescott FL. Solar powered V-2 vapour engine. Proceedings of the International Solar Energy Society Congress, Paris, France, 1973, Paper No. E7.
[14] Masson H, Girardier JP. Solar motors with flat-plate collectors. Solar Energy 1966;10(4):165–69.
[15] Girardier JP, Alexandroff M. Les moteurs solaires et l'habitat pour les zones arides, realisations actuelles et perspectives. Proceedings of the International Solar Energy Society Congress, Paris, France, 1973, Paper No. E82.
[16] Gupta CL, Santhanam VC, Reddy TA. Performance prediction model for a solar pump. Proceedings of the International Solar Energy Society Congress, New Delhi, India, 1978, pp. 1889–95.
[17] Daniels F. Power production with assemblies of small solar engines. ASME Winter Annual Meeting, Washington District of Colombia, 1971, Paper No. 71-WA/SO1-11.
[18] Mathur KN, Khanna ML. Arid Zone Programme Symposium on Solar Energy and Wind Power in Arid Zones, New Delhi, India, 1954.
[19] Amor MR, Raine JK, Tucker AS. Double diaphragm solar powered water pump. Proceedings of the International Solar Energy Society Congress, Denver, Colorado, USA, 1991, pp. 2141–6.
[20] Ariosoroff S, G. Tschanneri and co-workers, Community Water Supply (the Handpump Option). The World Bank, 1987, pp. 7–29.
[21] Jenness JR. Some considerations relative to a solar-powered savery water pump. Solar Energy 1961;5:58–60.
[22] Singer C, Holmyard EJ, Hall AR, Williams TI(editors) A History of Technology, vol. 4. New York and London: Oxford University Press, 1958. pp. 172.
[23] Rao DP, Rao KS. Solar water pump for lift irrigation. Solar Energy 1976;18:405–11.
[24] Sheldon JW, Crane RA, Kranc SC. Pumping action from heat-driven oscillations in a liquid-vapour column. Journal of Physics D: Applied Physics 1976;9:1419–25.
[25] Bhide VC. Solar energy utilization in India and abroad, National Productivity Council Conference on Industrial Uses of Solar Energy, Madras, 1975.
[26] Soin RS, Prasad IM, Rao DP, Rao KS. Development and performance of solar water pumps. Proceedings of the International Solar Energy Society Congress, New Delhi, India, 1978, pp. 1917–22.
[27] Maccracken CD. The solar powered thermopump. Proceedings of the Conference on Solar Energy—the Scientific Basis, Tucson, Arizona, 1955.
[28] Bold J. Solar powered water pump for the rural third world. Department of Mechanical Engineering, Laboratory for Energetics, Technical University of Denmark, Lyngby, Denmark.
[29] El-Mallah AA, Mohamad MA. Development of a solar energy operated water pumping system. Proceedings of the International Solar Energy Society Congress, Kobe City, Japan, 1989, pp. 2025–9.
[30] Bhattacharyya TK, Ramachandra S, Goswami AK. Low temperature bellow actuated solar pump. Proceedings of the International Solar Energy Society Congress, New Delhi, India, 1978, pp. 2118–21.
[31] Murphy CL. Review of liquid piston pumps and their operation with solar energy. ASME Paper, 1979, 79-Sol-4.
[32] Murphy CL. A solar liquid piston pump, Proceedings of Silwest 80 Conference, 1980, pp. 499–502.
[33] Venkatesh A. Solar thermal water pump. Proceedings of the International Solar Energy Society Congress, Denver, Colorado, USA, 1991, pp. 2135–40.
[34] Kwant KW, Rao DP, Srivastava AK. Experimental studies of a solar water pump. Proceedings of the International Solar Energy Society Congress, New Delhi, India, 1978, pp. 1917–21.
[35] Sudhakar K, Muralikrishna M, Rao DP, Soin RS. Analysis and simulation of a solar water pump for lift irrigation. Solar Energy 1980;24:71–82.
[36] Sudhakar K, Rao DP. Simulation and economic feasibility studies of solar water pump for lift irrigation. Proceedings of the National Solar Energy Convention, Brighton, 1978, pp. 664–56.
[37] Hariprakash Rao R. Theoretical and experimental investigations of a solar thermal water pump. Ph.D. thesis, Thermodynamics and Combustion Engineering Laboratory, Department of Mechanical Engineering, Indian Institute of Technology, Madras, India, 1990.
[38] Agarwal HC, Shreepal. A new design of a solar pumping system. Proceedings of the International Solar Energy Society Congress, New Delhi, India, 1978.

[39] Sumathy K, Venkatesh A, Sriramulu V. Heat-transfer analysis of a flat-plate collector in a solar thermal pump. Energy 1994;19(9):983–91.
[40] Sumathy K, Venkatesh A, Sriramulu V. The importance of the condenser in a solar water pump, Energy Conversion and Management 1995;36(12):1167–73.
[41] Sumathy K, Venkatesh A, Sriramulu V. Thermodynamic analysis of a solar thermal water pump. Solar Energy 1996;57(2):155–61.
[42] De Beni G, Friesen R. Spontaneous downward heat transport comparison tests of an improved system. Solar Energy 1993;50(1):27–34.